

International Space Station Major Constituent Analyzer On-orbit Performance

Ben D. Gardner¹, Philip M. Erwin² and Souzan Thoresen³
Hamilton Sundstrand Space Systems International, Pomona, CA, 91767

John Granahan⁴
The Boeing Company, Houston, TX, 77058

and

Chris Matty⁵
NASA Lyndon B. Johnson Space Center, Houston, TX, 77058

The Major Constituent Analyzer is a mass spectrometer based system that measures the major atmospheric constituents on the International Space Station. A number of limited-life components require periodic changeout, including the analyzer (ORU 02) and the verification gas assembly (ORU 08). The longest lasting ORU 02 was recently replaced after a record service length of 1033 days. The comparatively high performance duration may be attributable to a reduced inlet flow rate into the analyzer, resulting in increased ion pump lifetime; however, there may be other factors as well. A recent schedule slip for delivery of replacement verification gas led to a demonstration that the calibration interval could be extended on a short-term basis. An analysis of ORU 08 performance characteristics indicates that it is possible to temporarily extend the calibration interval from 6 weeks to 12 weeks if necessary.

Nomenclature

ISS = International Space Station
MCA = Major Constituent Analyzer
ORU = On-orbit Replaceable Unit
VGA = Verification Gas Assembly (ORU 08)

I. Introduction

THE MCA is a mass spectrometer based system designed to monitor nitrogen, oxygen, carbon dioxide, methane, hydrogen and water in the atmosphere of the International Space Station. It is the primary resource for ensuring that the oxygen and carbon dioxide levels on-board are maintained at safe levels, and the nitrogen partial pressure reading is used to monitor the ISS for cabin air leakage.

The MCA, shown in Figure 1, is designed as a series of seven subsystem modules (ORUs) that can be serviced or replaced individually in response to periodic maintenance requirements. Of these, ORU 05 – sample pumps, ORU 08 – verification gas assembly, and ORU 02 – mass spectrometer analyzer are the more commonly replaced subsystems. ORU 02 has thus far been the most commonly replaced ORU due to the limited life of the integrated ion pump used to maintain analyzer vacuum. Considerable attention has been paid to assessing the factors limiting the

¹ Project Engineer, Hamilton Sundstrand, 2771 N. Garey Ave., Pomona, CA 91767.

² Software Engineer, Hamilton Sundstrand, 2771 N. Garey Ave., Pomona, CA 91767.

³ Program Manager, Hamilton Sundstrand, 2771 N. Garey Ave., Pomona, CA 91767.

⁴ Insert Job Title, Department Name, Address/Mail Stop, and AIAA Member Grade for third author.

⁵ Atmosphere Revitalization Subsystem Manager, EC6 ISS ECLSS, NASA Lyndon B. Johnson Space Center, Houston, Texas 77058.

ion pump lifetime, as has been described previously¹. The improvements and modifications that can be applied to extend ORU life are being integrated into the MCA Depot Spares program.

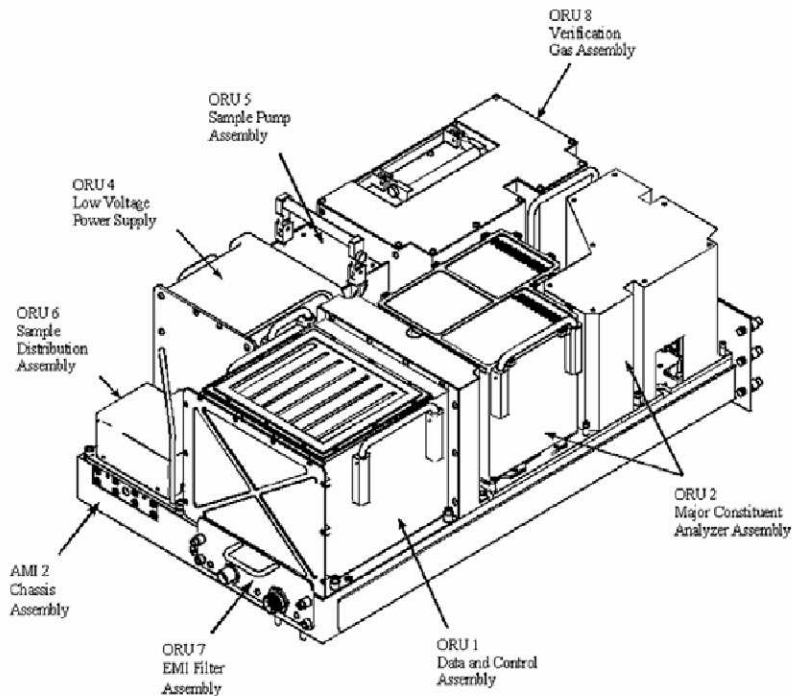


Figure 1: Major Constituent Analyzer

Here is reported the lifetime and performance characteristics of the most recent ORU 02s removed from service, and the application of any lessons learned during these ORU's lifetimes to an analysis of the current ORU 02 as a prediction of future performance. Also described is the predicted capacity of the current ORU 02 to provide accurate results with less frequent calibrations.

II. On-orbit Activities

A. ORU 02 F0001 Performance

ORU 02 is the mass spectrometer analyzer that forms the technological core of MCA. It is comprised of a gas inlet, ion source, single-focusing magnetic sector mass analyzer, six spatially arrayed ion detection electrometers and a 4 Liter/sec ion pump. The primary life-limiting items include the ion source filament (of which there are two) and the ion pump. To date, the ion pump has been the driving issue for ORU 02 periodic replacement.

The lifetimes of the ORU 02s that have been in service on orbit are listed in Table 1. While previous ORU 02s placed in service have lasted up to a year, the most recent ORU 02, serial number F0001 lasted 1033 days, which was a record for all ORU 02s thus far. Its increased lifetime may be due in part to the installation of a comparatively restrictive inlet that reduced the sample gas flow rate and reduced the load on the ion pump; although other factors may also be involved.

| ORU 2 Serial No. | Installed | Removed | MCA Serial No. | Comments |
|---------------------|-----------|---------|-------------------|---|
| F0001 | 2/12/01 | 6/23/01 | F0001 | Insufficient operating time to accumulate life data. |
| F0004 | 6/23/01 | 4/25/02 | F0001 | |
| F0003 | 9/1/02 | 9/29/04 | F0001 | Failed (end of life) with high ion pump current in September 2003. Used in Life Extending Mode until removal in September 2004. |
| F0002 | 9/30/04 | 2/16/06 | F0001 | Replaced due to increasing frequency of bad Zero Calibrations. |
| F0001 | 3/6/06 | 1/2/09 | F0001 | Removed before end of life to minimize impact to on orbit operations. |
| F0004 | 1/2/09 | 9/28/09 | F0001 | Operated 9 months. Had one shutdown due to high ion pump current spike. Was replaced before failure, to minimize impact to operations.. |
| Q0001 | 9/28/09 | -- | Q0001 | Currently in service on "Node 3" MCA (S/N Q0001) |
| F0003 | 2/8/10 | -- | F0001 | Not yet activated |

Table 1: ORU 02 on-orbit usage.

ORU 02 stability can be evaluated by tracking the electrometer correction values (ECVs) over time. ECVs are correction factors used to adjust MCA calculated partial pressures so that they agree with the composition of the calibration gas mixture. Each ORU 02, is calibrated on the ground to determine its gain characteristics for the detection of each of the major atmospheric constituents. The calibration is based on the response to a verification gas mixture of known, very accurately controlled composition. The resulting calibration values are then programmed into the ORU 02 prior to its Protoflight Acceptance Testing. Ideally each ECV should stay at or close to a value of 1.0000; however, it is known that the gain can change slightly over time for various reasons. Consequently, once on orbit, the ORU 02 is calibrated periodically using the same verification gas mixture. Any change in gain values is compensated for by taking the ratio of the expected response (partial pressure of each calibration gas constituents) to the measured response (MCA calculated partial pressures for each constituent) and using that value as a computational correction factor, the ECV, to adjust the result of the MCA's partial pressure calculations so that the MCA readout matches the known composition.

For example, a plot of ECVs for ORU 02 F0001 during its second deployment over a nearly three year period spanning 2006 – 08, is shown in Figure 2. As the plot shows, none of the ECVs remain at exactly 1.0000. The ECVs for N₂ and O₂ remain fairly constant over time, with the O₂ ECVs drifting downward slightly from about day 80 to day 300, and then upward from about day 400 to day 800, but never varying more than 2% over the three years, and never varying more than 1 part per thousand per month. The one exception to this is for the data point near day 400, when bad coefficients were loaded during a manual full calibration. The higher gain channels for methane, hydrogen, and carbon dioxide showed somewhat more sensitivity. Note that CH₄ and H₂ decreased over time, while the ECV for CO₂ rose significantly. It should be noted that the ECV drift rate varied for the previous ORU 02 as well.

The ECV drift rate should be evaluated periodically and the values in the ground-based post-processing adjusted if necessary, should it be determined that the actual gas composition is changing.

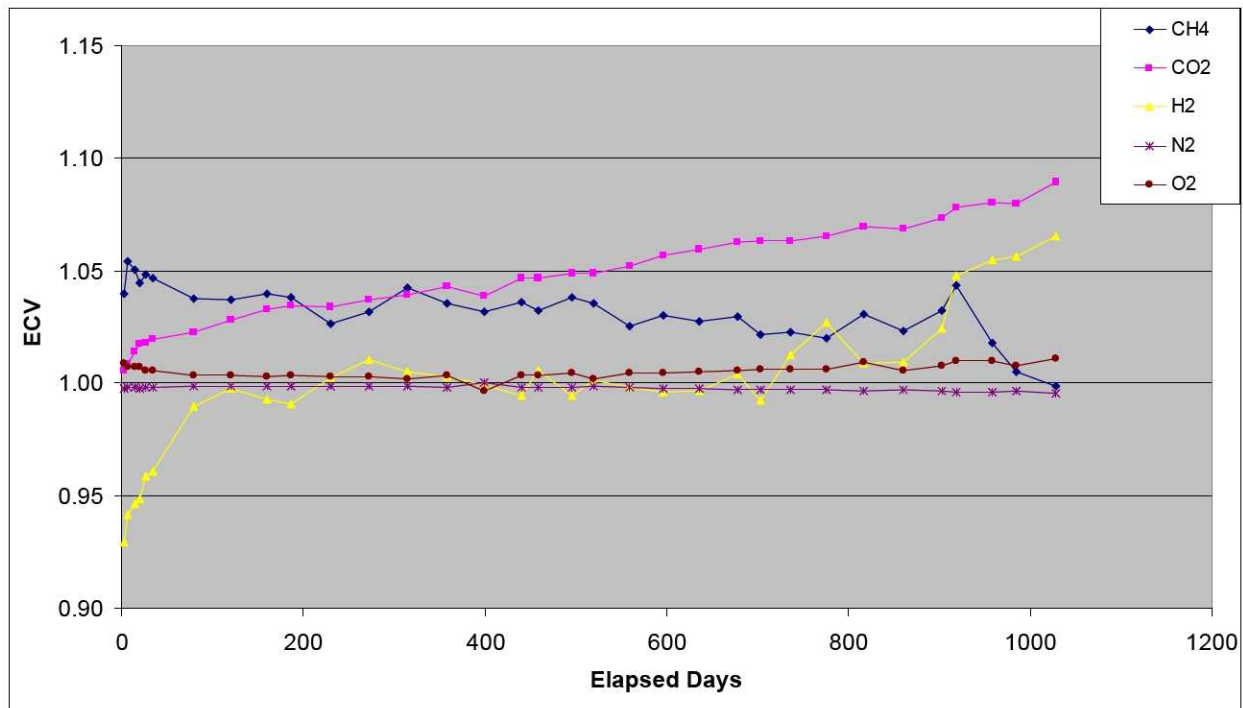


Figure 2: ECV trends of five major constituents for ORU 02 F0001

The ORU 02 ion pump is responsible for maintaining the operational vacuum level of the analyzer, and its degradation over time is the primary factor that limits the useful longevity of ORU 02. Ion pump current is a measure of pump load and therefore analyzer pressure, and is typically 60 – 100 μ Amps in an MCA. In the absence of any parasitic shunt current artifacts, a high pump current suggests a high pressure internal to the analyzer. The instrument is configured to automatically ‘safe’ the analyzer, protecting the source filaments, when the internal pressure is high enough to generate an ion pump current over 370 μ Amps, at which point it the MCA generates an error code and goes to FAIL state (shuts down). The projected lifetime of the ion pump on ORU 02 F0001 was predicted to be approximately 1400 days based on data obtained during its operation. The ORU 02 was removed from service prior to that point in anticipation of the impending end-of-life, and because of an increase in the number of nitrogen spikes that that produced transient currents above the 370 μ Amp threshold raised concerns that MCA shutdowns due to high ion pump current would occur.

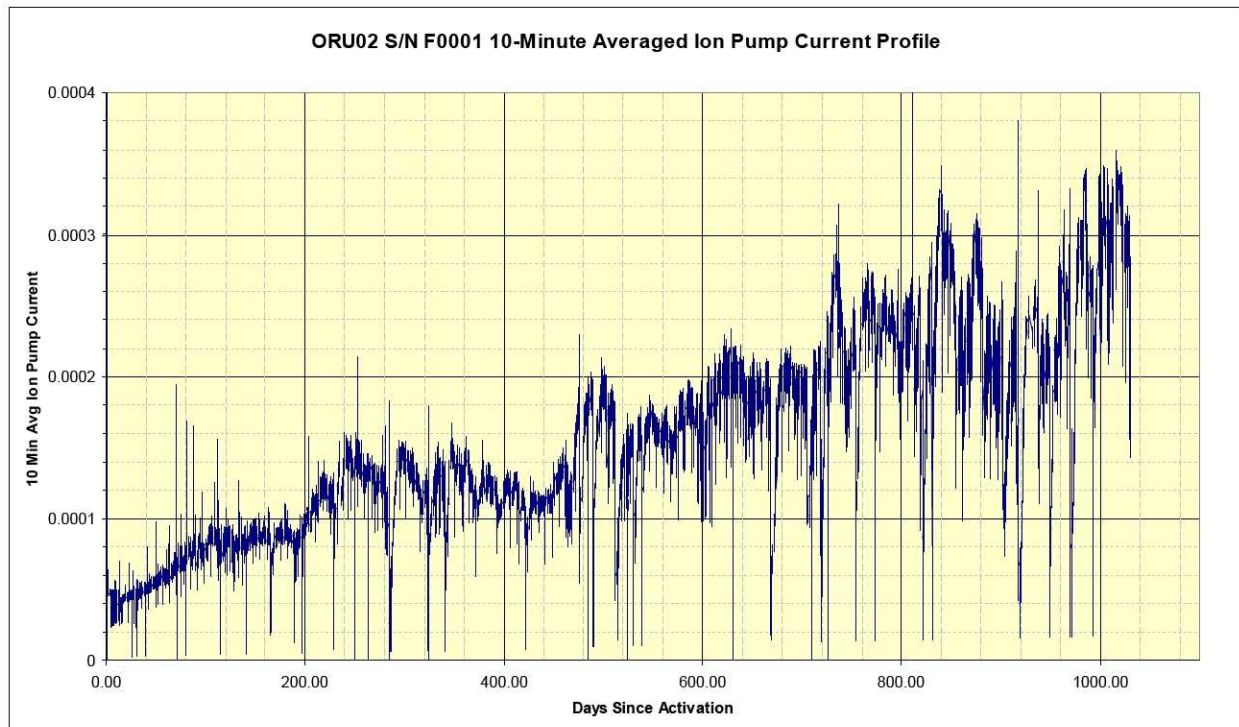


Figure 3: Ion Pump current over the lifetime of ORU 02 F0001.

B. ORU 02 F0004 Performance

ORU 02 F0004 was installed in the Lab MCA on January 2, 2009, replacing ORU 02 F0001 which was returned to ground.

1) Problems with initial activation.

The first two startup attempts failed (timed out) because MCA did not achieve OPERATE state within 47 minutes. It is believed that this is because the ORU 02 sat idle for an extended period (4+ years) before activation and had somewhat more than normal moisture build-up in its vacuum system. The third startup attempt resulted in MCA getting to OPERATE state but went to FAIL state after 31 minutes when a pressure sensor went negative. It was later determined that the crew had left the HV02-valve closed in the verification gas assembly. As a result, the sample line pressure was pulled down during the sample pump checks as a part of the startup sequence. The crew later opened the valve and MCA startup was completed.

During the attempt to recover from FAIL state, ground command sent a functional override command (FOC) as part of a procedure to recover from FAIL to IDLE state. Functional override commands are a two-step process requiring that an initial command be sent, then after receipt of a “waiting confirmation” status is received from the MCA, a confirmation command is sent. Upon sending the confirmation, ground did not receive the expected “waiting” status, and thus could not send the confirmation command. After troubleshooting involving power cycling the MCA and sending effector override commands, the MCA was successfully started. The cause of the functional override commanding anomaly has not been determined.

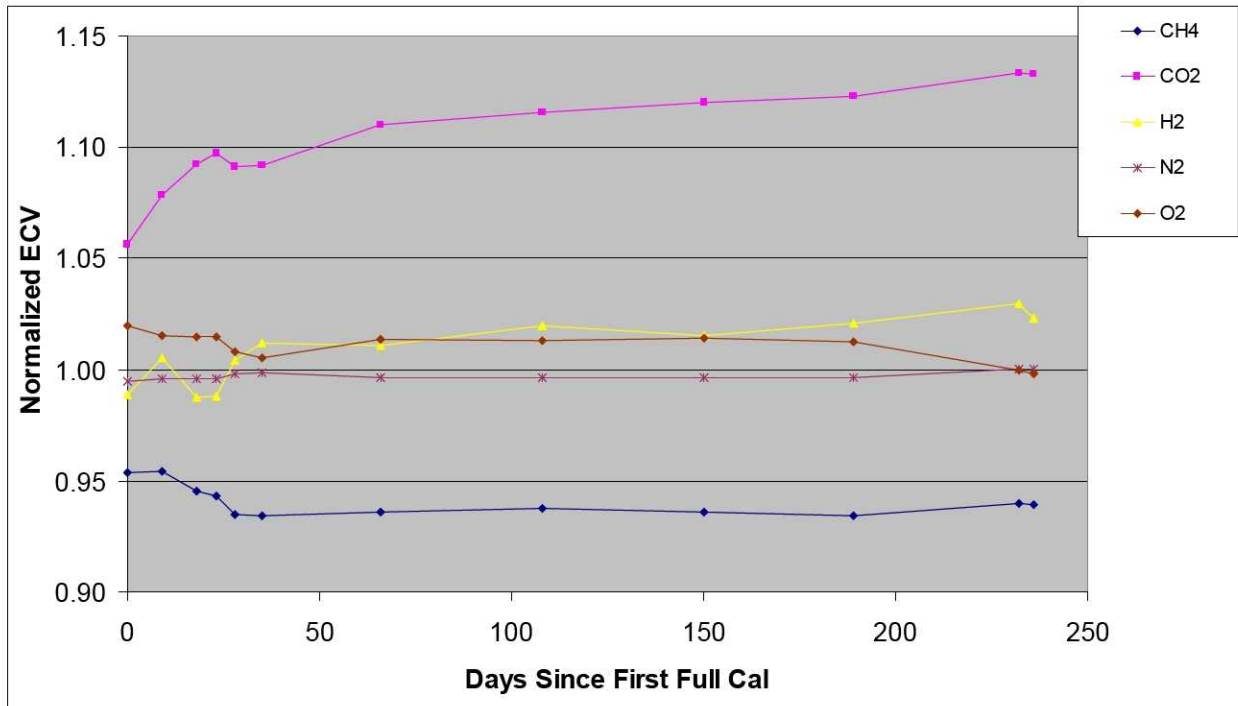


Figure 4: ECV trends of six major constituents for ORU 02 F0004 in 2009

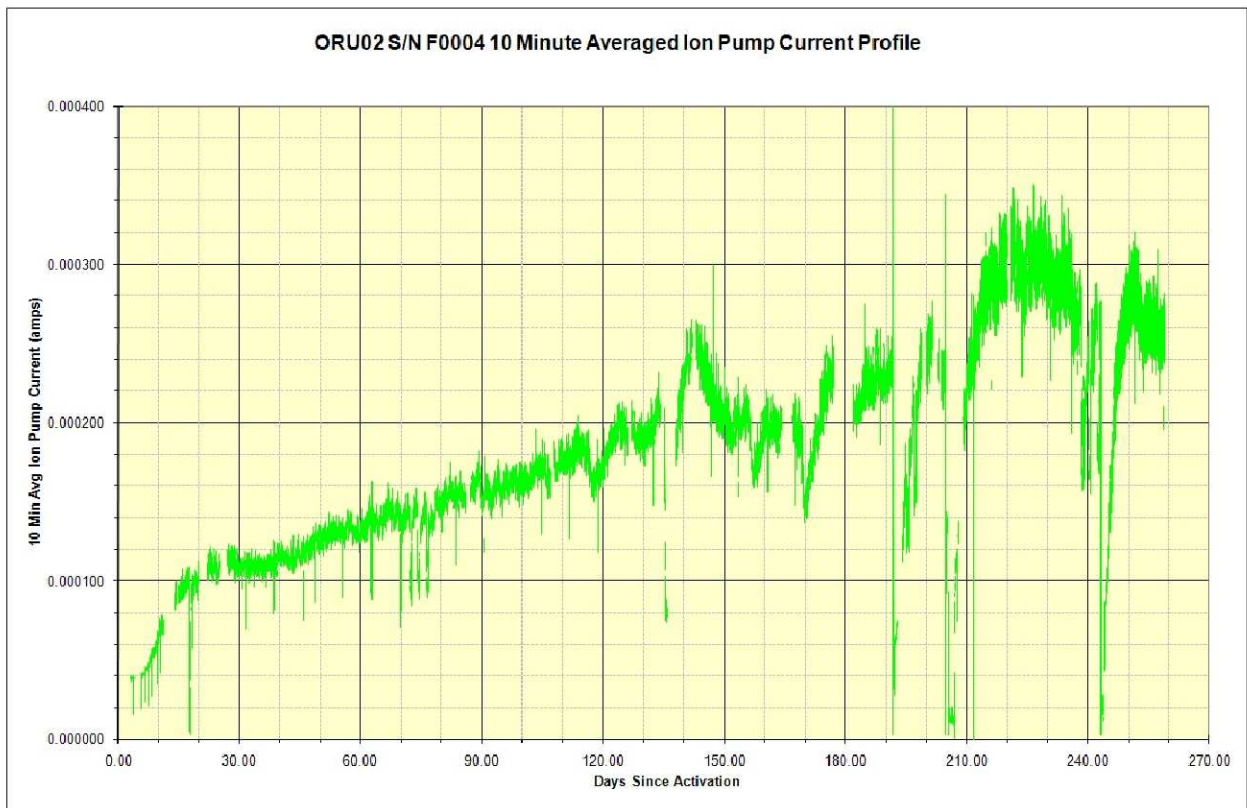


Figure 5: Ion pump current for ORU 02 F0004

C. ORU 02 Q0001 Performance

Thus far ORU 02 Q0001, which is currently in operation in the Node 3 MCA, is performing nominally. The ECVs have drifted down slightly, including the ECV for CO₂, which is unusual. Initial performance trends for the ion pump suggested that it might last on the order of 300 days. However, more recently the ion pump current has decreased, potentially increasing the expected lifetime.

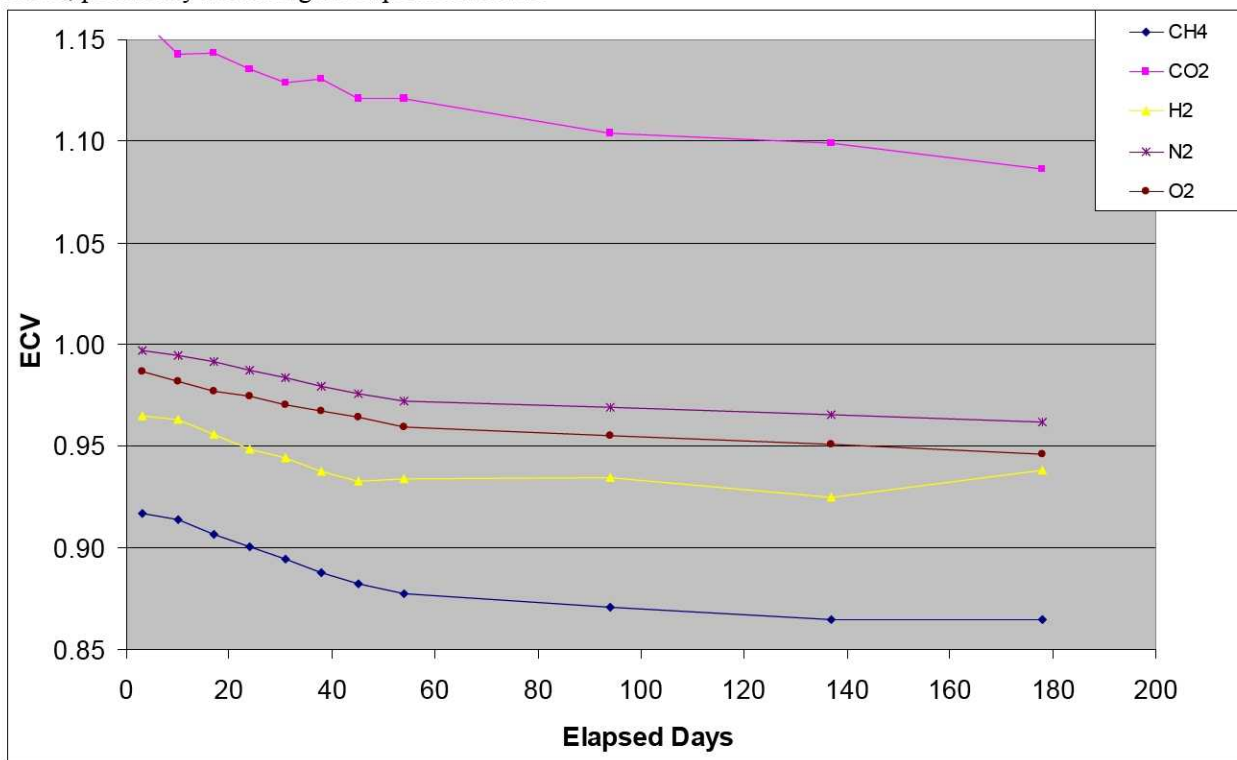


Figure 6: ECVs of five major constituents for ORU 02 Q0001.

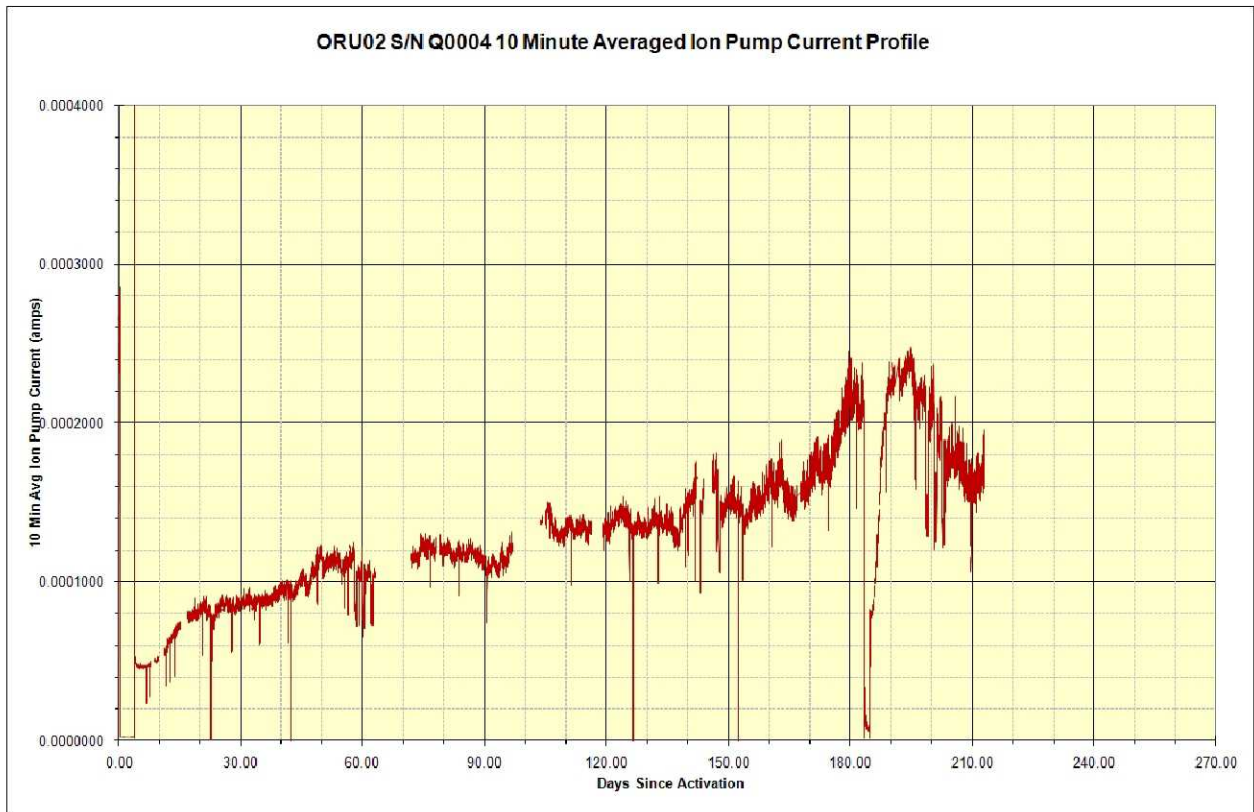


Figure 6: Ion Pump Current for ORU 02 Q0001.

D. ORU 08 F0002 Verification Gas Conservation

ORU 08 F0002 was in service from 12/21/05 to 9/22/09. Because the supply of verification gas was running low and at risk for depletion in August, 2009, and the replacement ORU 08 had not been launched, several conservation steps were taken to preserve the remaining verification gas. These included extending the calibration interval from 6 to 8 weeks (based on accuracy drift rate estimates and judgment) beginning in May, 2009, and lowering the minimum allowable VGA pressure for calibrations from 100 to 65 psi. (these steps were implemented per CHIT 7645). Both steps were originally intended to apply only while ORU 08 F0002 was installed; however, subsequently, the MCA Management Flight Rule was changed to make the 65 psi limit permanent. We have returned to the 6 week calibration interval now that ORU 08 F0002 is no longer in use.

The logic used to determine the extent to which the calibration interval could be extended was based both on an analysis of the calibration process and the performance of ORU 02 F0004, which uses the verification gas and was in service in August, 2009. There are two sets of parameters that affected the calculated partial pressures of the measured atmosphere constituents; electrometer background values and the ECVs described earlier. The electrometer background values are essentially offsets that must be subtracted from the electrometer signals, and these are measured each week using a routine known as zero calibration. The routine essentially closes the analyzer inlet and measures the electrometer levels when no gas is entering the system. The ECVs, on the other hand, are determined every 6 weeks as part of a full calibration. The full calibration consumes some of the verification gas mixture that is stored in a pressurized container in ORU 08. Thus it was desired to stretch the time only between full calibrations to conserve the remaining verification gas until the replacement ORU 08 could be made available. In order to do that, though, the performance of the current ORU 02 must also be evaluated to determine the impact to MCA accuracy over time as the full calibration interval is lengthened.

While the question of how long the calibration interval can be extended relates specifically to the performance of ORU 02 F0004, this ORU 02 had only been in service for slightly over 100 days. Furthermore, as of May 1, 2009, it had performed only two full calibrations approximately 70 days or longer after power up. Consequently, the probable long-term stability of this ORU 02 had to be inferred using the performance of previous ORU 02s as a guide. The previous ORU 02, F0001, appeared to be the most similar to F0004 of any ORU 02s at that time.

Estimation of ECV stability is based on the ECVs from the full calibrations occurring 69 and 111 days after power up. Figure 4 shows the ECV trends for ORU 02 F0004. The H₂O ECV is approximately 3.3. The H₂O ECV values were rescaled by multiplying by 0.3 so that they would fall in the graph area.

For ORU 02 F0004, the CO₂ ECV rate of change is 1.4E-4 per day. On the previous ORU 02, the average rate was about 6E-5 per day. So the rate of change of the CO₂ ECV with this ORU 02 is still about two times the long term rate of the previous ORU 02. However, the rate appeared to be decreasing, and it was expected that it would stabilize to the same rate as the previous ORU 02.

Table 2 shows the apparent ECV rates of change and the 12 week change of partial pressure given that rate of change. The rates of change are per day. The twelve week change assumes the ECV changes continuously at the given rate. The twelve week change also assumes typical atmosphere composition of approximately 585 mmHg N₂, 160 mmHg O₂, 11 mmHg H₂O, 4 mmHg CO₂, 0.5 mmHg H₂, and 0.5 mmHg CH₄.

| Constituent | F0001 Sensitivity Drift, dP/P | 12 Wk Change (Torr) | F0004 Sensitivity Drift, dP/P | 12 Wk Change (Torr) |
|------------------|-------------------------------------|------------------------|-------------------------------------|------------------------|
| CH ₄ | -1.70E-05 | 0.0007 | 4.00E-05 | -0.0017 |
| CO ₂ | 6.40E-05 | -0.0214 | 1.40E-04 | -0.0465 |
| H ₂ | 2.70E-05 | -0.0011 | 2.10E-04 | -0.0087 |
| H ₂ O | 2.90E-04 | -0.2616 | -5.40E-03 | 1.3 |
| N ₂ | -3.10E-06 | 0.1524 | 2.80E-06 | -0.1376 |
| O ₂ | 7.50E-06 | -0.1007 | 1.04E-05 | -0.1397 |

Table 2: Twelve Week Partial Pressure Change.

The least stable component is water. An error in water leads to systematic errors in the other components. This is because the total quantities of the components are renormalized to add up to the correct total pressure. If H₂O is over-reported by 1.3 Torr, then after renormalization, N₂ will be under-reported by about 1 Torr and O₂ will be under-reported by about 0.3 Torr. The total of all partial pressures will still add up to the expected total pressure, so the error will not be readily apparent.

The partial pressure results during a period longer than six weeks can be calculated by updating the calculations that are used to obtain the improved accuracies. The MCA Accuracy Calculations spreadsheet, Hamilton Sundstrand part no. 93-0099 version 1.10, was updated with ECV slopes shown in Table 1.

Based on the stability of ECV trends shown for ORU 02 F0001, the ECVs should follow the trend or be closer to zero. The last two full calibrations gave values that produced a calculated ECV change slope of -5.4E-3, but the probable overall tendency was predicted to be closer to the 2.9E-4 slope of the previous ORU. If the ground-based post-processing of the MCA readings is adjusted according to the updated MCA Accuracy Calculations spreadsheet, then the errors produced by ECV drift should be no worse than the values shown in Table 2. These values are within the accuracies predicted after post-processing.

Lengthening the interval between full calibrations to 12 weeks is unlikely to result in a significant increase in the errors of the calculated partial pressures. Based on the previous ORU 02, the ECVs seem to drift at a near constant rate over periods of about 100 days.

E. Node 3 MCA Launch

A second MCA has been delivered to the ISS. The "Node 3" MCA, installed in the Node 3 AR rack, was launched on Shuttle mission STS 128 (17A) in August, 2009. Also launched on this flight were ORU 02 F0003, ORU 05 F0003, and ORU 08 F0001 to serve as on-orbit spares. The MCA was launched less ORU 01, the data and control assembly, which is currently being upgraded with new firmware. ORU 01 Serial No. F0001, with new firmware installed, was launched on shuttle mission STS 131 (19A).

The Node 3 MCA is intended to be located in the ISS Node 3. However, to accommodate a need for improved CO₂ removal, the Node 3 Atmosphere Revitalization (AR) rack (including the Node 3 MCA less ORU 01) was installed in the US Lab (at the LAB1D6 location) on 9/22/2009, while the original Lab AR Rack containing the Lab MCA (S/N F0001) was removed and temporarily stowed. The ORU 01 Q0001 originally in the Lab MCA was transferred to the Node 3 MCA on 9/25/09, and that MCA was activated on that same date. Improved accuracies were implemented for ORU 02 S/N Q0001 on 11/16/09 per CHIT 7975.

ORU 02 S/N F0004, ORU 05 S/N F0002 and ORU 08 F0002 were removed from the inactive Lab MCA in the Lab AR Rack in the JEM on 2/8/2010. The removed ORU 05 and ORU 08 were returned to ground on 20A. The removed ORU 02 was returned to ground on 19A.

III. Conclusion

A conclusion section is not required, though it is preferred. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions. *Note that the conclusion section is the last section of the paper that should be numbered. The appendix (if present), acknowledgment, and references should be listed without numbers.*

Acknowledgments

References

¹Gardner, B. D., Erwin, P. M., Lee, W. T., Tissandier, A. M. and Thoresen, S. M., "Improving the measurement Accuracy of Water Partial Pressure Using the Major Constituent Analyzer," *39th International Conference on Environmental Systems*, Savannah, GA 2009.